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Distribution of Oolitic Sediment Along a Beach-to-Offshore Transect, Pigeon Cay, Cat Island, Bahamas: New Insights Into Modern Ooid Formation

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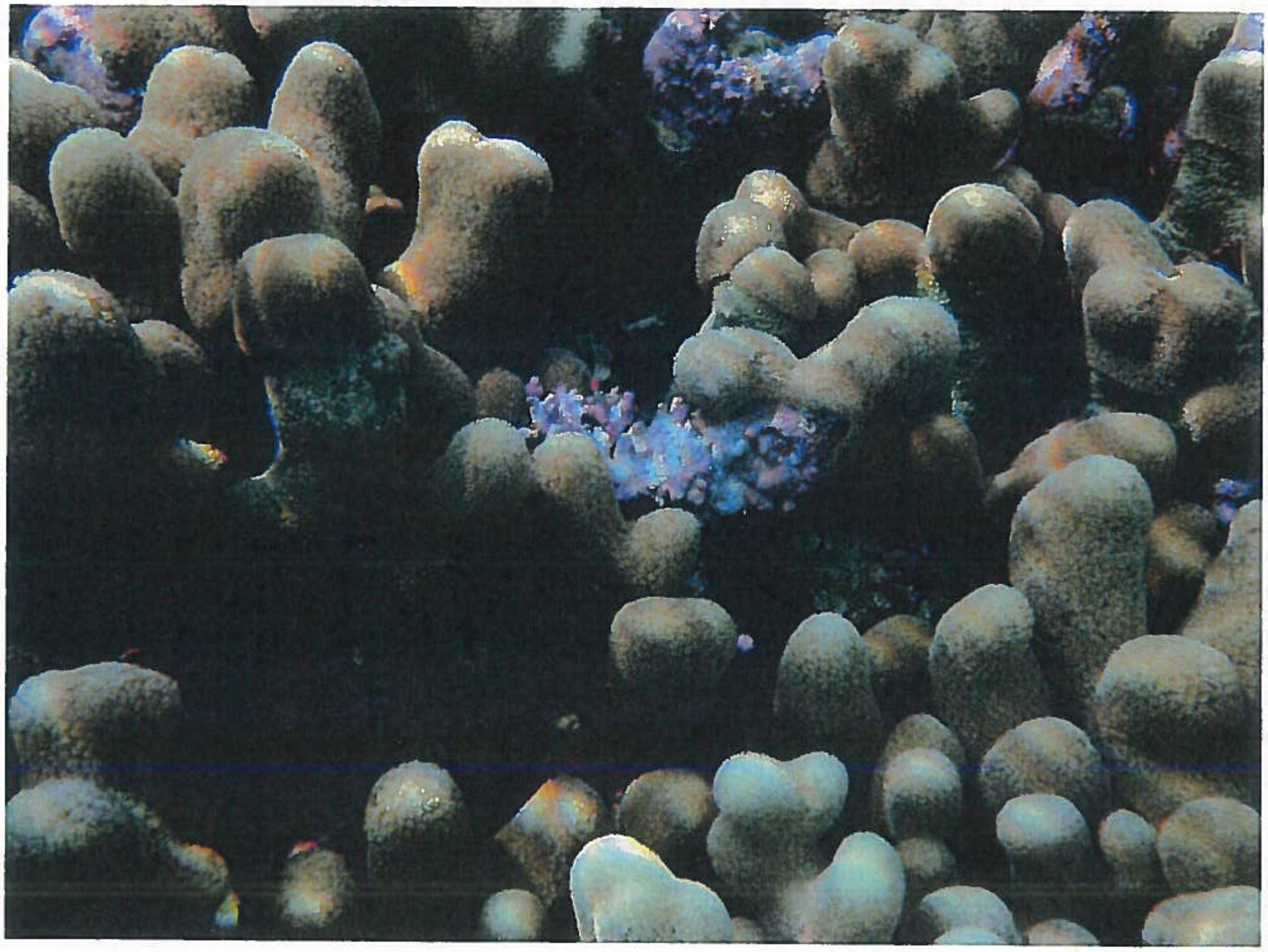

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(Cover photo: *Porites* coral encrusted by red algae in waters of San Salvador, Bahamas by Pascal Kindler)

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ABSTRACT

Ooids are a common component of ancient carbonate rocks, but their origin and distribution in Holocene deposits and modern carbonate sands are not fully understood. Even though ooids are well documented from several localities in the Bahamian Archipelago, their occurrence on Cat Island has not been previously studied in detail. In this study we examined the composition and texture of beach sand and six sediment samples collected from the sea floor at approximately 50-meter intervals along an estimated 300 m transect at Pigeon Cay, Cat Island. We found substantial variation in sediment texture and composition along the transect. Beach and nearshore areas are dominated by well-sorted and fine-grained sand composed of spherical to elliptical ooids. In the mid-reach of the transect, between 150 to 200 m offshore at approximately 2 m depth, there is a distinct change in sediment composition toward coarse-grained, poorly sorted sand with more skeletal fragments and abundant angular and irregular grapestone aggregates of ooids, peloids and skeletal fragments in micritic matrix. Such aggregate grains dominate the rest of the transect to about 3.5 m water depth. These observations suggest that off Pigeon Cay, ooids form within a relatively narrow, wave-swept shoreface and shallow nearshore zone that visually appears to be largely devoid of seagrass, calcareous algae and other sediment stabilizers. From this environment, storm waves and currents transport ooids onshore where they are further sorted and lithified into beachrock and eolianite. Ooids also are transported farther offshore into deeper and less energetic environments, where skeletal fragments, peloids and carbonate mud are also present and lithify into aggregate grains or grapestones. This study documents a new example of modern ooid formation and deposition along the leeward side of a small Bahamian island in an environment that typically would be regarded as unsuitable for prolific ooid production due to relatively low energy and/or small areal extent.

INTRODUCTION

Ooids are an important sediment constituent of Archean to recent strata, and their Holocene occurrences have been extensively studied throughout the Bahama Archipelago (e.g., Newell et al., 1960; Ball, 1967; Boardman et al., 1993; Rankey et al., 2006; Reeder and Rankey, 2008; Kindler and Hine, 2009; Duguid et al., 2010). Although not specifically mentioned in the study of platform sediments on Cat Island, Bahamas, by Dominguez et al. (1988), ooids have been noted as a major component of carbonate sand on Cat Island (Lind, 1969; Kindler, 1992; Kindler and Hearty, 1996; Mylroie et al., 2006). The presence of Cat Island on the eastern (windward) margin of the Great Bahama Bank, together with Eleuthera Island, Exumas Cays and Long Island, has been attributed to the prevailing easterly trade winds (Kindler and Hine, 2009; and references therein). Kindler and Hine (2009) noted the "paradoxical" presence of abundant Pleistocene and Holocene oolitic limestone on these islands in the absence of a recent, prolific ooid source. To better understand the origin and distribution of ooids in such settings, our current study compares the

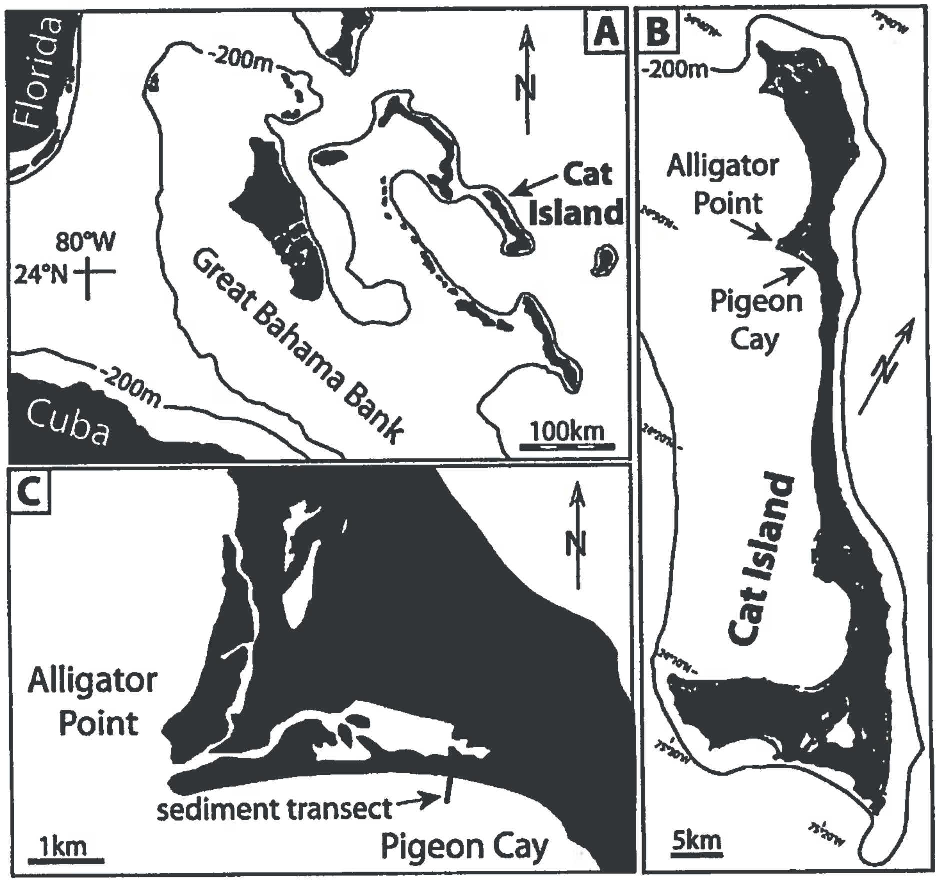


Figure 1. Maps of the study area. A) Location of Cat Island along the eastern margin of the Great Bahama Bank (modified after Kindler and Hearty, 1995). B) Location of Pigeon Cay and Alligator Point on the western (leeward) side of Cat Island. C) Sediment transect was about 300 m long and oriented perpendicular to the south-facing Pigeon Cay beach.

composition and texture of ooid-rich beach sand to sediment samples collected from the sea floor along a transect at Pigeon Cay, Cat Island (Figure 1). The study area is on the western (leeward) coast of Cat Island, so we specifically evaluate the potential for ooid formation and accumulation along a relatively low-energy shore characterized by a narrow shelf. We examined ooid-rich sediment in this shallow nearshore area in relation to physical characteristics of these environments. Our observations were compared to previous descriptions of sediment type and distribution on and around Cat Island (Lind, 1969; Dominguez et al., 1988), and related to the proposed models of ooid formation in similar settings (e.g., Lloyd et al., 1987; Wanless and Tedesco, 1993; Kindler and Hine, 2009). The results of this small-scale preliminary study reveal interesting and important information about the formation of ooids and their subsequent transport, deposition and lithification. This study also provides the foundation for conducting more extensive and in-depth research on Cat Island in the future.

STUDY AREA

Cat Island is a narrow and elongated, NNW-SSE trending island located between the North Atlantic Ocean to the east and Exuma Sound to the west (Figure 1). The western coast of the island has generally low wave-energy conditions; prevailing easterly winds keep the offshore and nearshore waters relatively calm except for low (up to 0.5 m) swells (Lind, 1969). In summer months, variable wind conditions occur during local storms. Most onshore (westerly) winds occur in winter and are related to passing cold fronts (Kindler and Hine, 2009). The shallow nearshore area prevents large waves and swells from reaching the coast; water is about 4 m deep several hundred meters offshore, and within 100 m offshore depth is commonly only 1-2 m (Lind, 1969; Dominguez et al., 1988). The largest waves that reach shore are generally less than 1.5 m high (Lind, 1969). Although rather small, such plunging and spilling storm breakers can cause noticeable erosion of the leeward beaches (Lind, 1969).

The carbonate shelf to the west of Cat Island is relatively small (<800 km^2) and with a thin sediment cover (Dominguez et al., 1988). This shelf gradually slopes westward to 20-30 m water depth about 15 km offshore followed by a precipitous drop into Exuma Sound without an intervening barrier rim. The absence of the barrier rim is attributed to the shelf margin being below the zone of maximum carbonate production and characterized by very limited coral reef development (Lind, 1969; Dominguez et al., 1988). This relatively deep shelf has been interpreted as an incipiently drowned Holocene carbonate platform unable to "keep-up" with Holocene sea-level rise (Dominguez et al., 1988). The presence of a rim-free margin exposes the interior shelf to open marine conditions and to current circulation that may be controlled by the scallop-shaped, deep-water shelf-margin reentrants (Freeman-Lynde and Ryan, 1985; Dominguez et al., 1988). This circulation may in turn control sediment facies distribution, which seems to accumulate in an oblique to perpendicular (rather than parallel) orientation to the shelf edge with the exception of shelf-margin skeletal sands (Dominguez et al., 1988). Longshore currents and large-scale eddy currents that sweep broad expanses of the shelf have also been proposed as important controls on sediment distribution and transport judging from sand waves and other large, current-formed submarine sedimentary structures observed on aerial photographs (Lind, 1969; Dominguez et al., 1988). Longshore currents, produced by the interaction of offshore winds and tides, likely played an important role in the formation of barrier spits (such as the projecting Alligator Point barrier) along the west coast of the island (Figure 1) and the subtidal sand shoals extending offshore from such cuspate headlands (Lind, 1969).

There is relatively little (0 to 4 m thick) unlithified sediment on the leeward Cat Island shelf, and the thickest sediment accumulations are along the subtidal sand shoals and the shelf edge (Dominguez et al., 1988). Sediment on the shelf is dominated by sand mixed with some gravel-size particles; mud content is minor (1-6 %; Dominguez et al., 1988). Biogenic sediments consist mainly of mollusk shells, foraminiferal tests and calcareous algal fragments, and of considerable importance, ooids and aragonite needles (Lind, 1969). The relatively highly degraded (microbored and micritized) nature of Cat Island shelf sediments, and their rather old bulk radiocarbon dates (inner and middle shelf ~2,500 yrs old; outer shelf ~1,000 yrs old), prompted Dominguez et al. (1988) to refer to them as "relict" sediments. Their overall small volume is attributed to relatively low rates of carbonate production on this "drowned" shelf and is not considered to be related to efficient offbank sediment transport because of the paucity of shelf-derived sands along the deep-water slope in Exuma Sound adjacent to the Cat Island shelf (e.g., Crevello et al., 1984). Although of limited volume, the bank sediment is the principal source of Cat Island beach and dune sands, which can be transported by storm surges and waves of sufficient energy from the shelf towards the leeward island beaches (Lind, 1969).

Pigeon Cay beach is one such south-facing beach located to the east of Alligator Point (Figure 1). In January 2009, this beach was rather narrow and featureless, about 10 m wide, gently and uniformly southward sloping, lacked a prominent berm and backshore, and transitioned into low-relief vegetated dunes to the north (Figure 2). A small (about 20 cm)

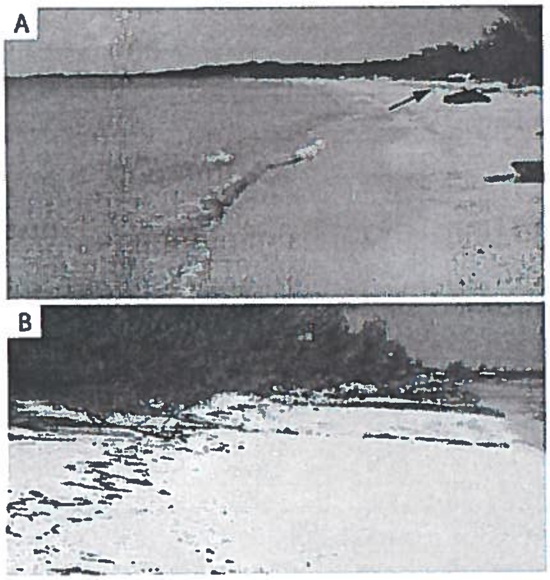


Figure 2. Field photographs of the Pigeon Cay beach in January 2009. A) View west toward the tip of Alligator Point. The beach is about 10 m wide and slopes gently and uniformly seaward from the adjacent vegetated, low relief dunes. Some shells are scattered along the high-water line and the remaining beach sediment is composed exclusively of ooids. Small rock exposures are present along the beach and an erosional scarp (about 0.2 m high) from a recent winter storm is visible high on the beach (arrow). The fair-weather waves are <0.2 m high and are slightly oblique to the W-E trending shore; B) View east showing low relief exposures of Holocene deposits in the distance, and the fine-grained, well-sorted ooid sand of the Pigeon Cay beach.

erosional scarp located relatively high on the beach (Figure 2A, see arrow) illustrates a typical effect of winter storms. Small outcrops of Holocene deposits are present along this section of the beach (Figure 2B). Besides some small concentrations of larger shells, the beach sand at Pigeon Cay is dominated by ooids.

The extent of the shallow nearshore environment with potential for sediment accumulation is illustrated on the bathymetric maps of the Cat Island shelf by the 4 m contour paralleling the southern coast of Alligator Point and Pigeon Cay at about 800 m offshore, and outlining sand shoals westward off Alligator Point (Dominguez et al., 1988). In addition, the southward-facing slopes of Alligator Point offer excellent rock exposures interpreted to represent the windward flank of a Holocene dune-ridge complex (Mylroie et al., 2006). This complex consists of eolianite deposits composed dominantly of fine-grained ooid grainstone, in contrast to the skeletal-peloidal grainstones of Holocene eolianites common elsewhere in the Bahamas. Mylroie et al. (2006, p. 31) proposed that "ooid sands presumably originated in the leeward Exuma Sound shelf of Cat Island and were moved inland by wave and wind transport." Therefore, the Alligator Point–Pigeon Cay area offers a unique setting in which to investigate present-day mechanisms and sites of ooid formation and their relationships to Holocene and recent sediment distribution patterns.

METHODS

Sediment samples were collected in January 2009 during calm conditions (with fair-weather waves <0.2 m high and slightly oblique to the W-E trending shore; Figure 2), but the water was very murky (milky white) due to the presence of suspended sediment from windy, stormy conditions just days earlier, characterized by waves 0.5 to 1.0 m high. This poor visibility (of only about 1 to 1.5 m) precluded making detailed underwater observations. For this reason, the distances and water depth along the chosen sediment sampling transect were estimated. The transect was perpendicular to the shore at Pigeon Cay and was generally trending N-S (Figure 1C). We collected one sand sample from the beach and compared its composition and texture to six sediment samples collected from the sea floor at approximately 50 meter intervals along the transect, which was about 300 m long. Underwater surface sediment samples were collected using a rigid plastic container and by making one sweep across several wave ripples perpendicular to their crests. Sand was dried in the laboratory and examined under a binocular microscope. Sand mounts were made using clear epoxy and thin sections were prepared for petrographic analysis.

OBSERVATIONS

A summary of our observations of sediment composition and texture along the transect at Pigeon Cay is presented in Figure 3 and illustrated in the accompanying Figure 4. The beach sand is fairly well sorted and composed of regular, well-rounded, spherical to elliptical ooids with predominantly peloidal nuclei surrounded by cortices consisting of concentric laminae made of tangentially arranged aragonite crystals. Some peloids are also present, and judging from their texture, they are likely micritized ooids. Aside from serving as nuclei of superficial ooids, skeletal fragments are rare (foraminifera, mollusks, calcareous rods). Ooids are mainly fine to medium sand size (100-400 μm) with rare coarse sand grains (up to 600 μm) representing compound ooids (coated grains with 2 to 3 ooids as a nucleus), peloids, and grapestone grains (aggregates of ooids, peloids and skeletal fragments). Microborings are common and many ooids are at least partially micritized, but complete micritization is rare. Commonly, the outer cortices are well preserved and interiors of ooids are bored and micritized. There was no obvious micrite present in the sediment.

Despite poor underwater visibility, we observed that the offshore area along the transect was a barren sandy bottom generally devoid of marine algae and seagrasses. The sediment surface was characterized by wave ripples and sand waves with crests generally parallel to each other and trending subparallel or slightly oblique (WNW-ESE) to the shoreline.

The sample collected about 50 meters from the beach has the same components as the beach sand but with a greater proportion of coarse sand represented by skeletal and aggregate grains. Ooids range from 100-500 μm in size, and aggregate grains are mainly 500-700 μm in diameter. The majority of skeletal fragments (mainly mollusks) are 1-1.5 mm in size, with the largest at 3.5 mm in diameter.

In the sample collected about 100 m offshore, the trend of increasing skeletal fragments and aggregate grains continued; this sample contains more irregularly shaped larger grains and the sediment is therefore coarser, not as well rounded, and more poorly sorted. Ooids are still common and range in size from 150-500 μm, but are dominated by medium (over fine) sand-size grains. Coarse sand consists predominantly of 700-900 μm aggregate grains, and skeletal grains reach up to 5 mm in diameter.

Similar trends in increasing grain size were observed in the sample from about 150 m offshore. Fine to medium-grained sand composed of single ooids, 150-300 μm in diameter, is less common here, and the majority of ooids are of coarse-sand size, reaching up to 700 μm in diameter. Aggregate grains up to 1 mm in size also become more abundant.

In general, the samples collected about 150 and 200 m offshore reveal the greatest change in sediment composition and texture. Approximately 200 m offshore at about 2 m water depth, the sediment changes from generally finer, better-sorted oolitic sand to coarser angular sand dominated by aggregate grains and skeletal fragments. Here, the sediment is mainly coarse- to very coarse-grained sand with a substantial proportion of granule size material. Very coarse sand-size complex aggregate grains composed of multiple ooids, peloids and skeletal grains (mainly 700 μm to 1.7 mm; maximum 6 mm in diameter) become the dominant sediment component. Skeletal material is present mainly in aggregates or as individual grains (up to 10 mm in size) with micritic coatings. Individual ooids (150-600 μm in size) are still present, but only constituted about 20% of the sediment.

Sediment of the sample collected 250 m offshore is similar to that from 200 m, but is even coarser and more poorly sorted. Individual ooids (up to 400 μm in size) become less abundant (10-20%), and the sediment is mainly composed of coarse to very coarse sand-size aggregate grains (mainly 800 μm to 1.6 mm, and maximum 6 mm in diameter) made up of multiple ooids, peloids and skeletal material in a micritic matrix. Aggregates range from very friable to well-lithified grains or lithoclasts with abraded outer edges. Skeletal fragments (up to 8-10 mm in size) are common, either in aggregates or as individual uncoated grains or with micritic coatings.

The last sample along the transect, collected about 300 m offshore at approximately 3.5 m water depth, is very similar to those collected at 200 and 250 m. Individual ooids of fine- to medium-sand size are even less common and constitute only about 10% of the sediment, which is mainly composed of coarse to very coarse sand-size aggregate grains and skeletal fragments. Aggregate grains range in size from 600 μm to 6 mm, and are mainly 1-2 mm in diameter. Skeletal fragments are still a common component of aggregates, but the amount of individual skeletal grains both unaltered and superficially coated/micritized further increases, although the grains appear slightly smaller in size (up to ~4 mm). Some sparite was noticed in aggregate grains from this sample; fibrous acicular aragonite is mainly present in intraskeletal voids, and fine-crystalline, clear equant calcite was observed in only one instance between ooids in a well-lithified aggregate grain (lithoclast).

INTERPRETATIONS AND DISCUSSION

Sediment texture and composition change substantially along the transect (Figures 3 and 4). The beach sand is dominated by fine-grained and very well-sorted ooids of regular spherical to elliptical shape whereas about 300 m offshore the sand is coarse-grained, poorly sorted, contains more skeletal fragments, and is dominated by angular and irregular grapestone aggregates of ooids, peloids and skeletal fragments in a micritic matrix. Between about 150 and 200 m offshore there is a distinct change from the generally poorly sorted aggregates in deeper water to more rounded and sorted ooids closer to the shore.

These observations suggest that at Pigeon Cay ooids form within a relatively narrow (less than about 200 m wide), wave-swept beach shoreface and shallow (less than about 2 m) nearshore environment devoid of calcareous algae and other sediment stabilizers. Storm waves and currents transport ooids onshore where they can be sorted further and lithified into beachrock and eolianite deposits. Ooids transported to deeper and less energetic offshore settings are deposited together with peloids, skeletal fragments and carbonate mud, and lithified into micritic aggregate grains or grapestones.

Although no ooids from Pigeon Cay were dated, good preservation of some of the ooids and especially their outer cortices suggests that ooids are actively forming in this area. The variable amount of micritization of ooids by microboring also suggests that ooids of various ages might be mixing in this environment and that water agitation during ooid formation varied between persistent and intermittent. Periods of agitation alternating with more quiet conditions are not surprising given the prevailing easterly winds and rather low-energy conditions along the leeward side of the island during most of the year and the occurrence of strong westerly winds related to cold fronts that can significantly impact the area in the winter. A barren sandy bottom, the cloudiness of the water, likely related to suspended fine-grained sediment, and the occurrence of wind ripples and sand waves offshore at Pigeon Cay also indicate that wind-generated waves and currents move sediment frequently in this area. Therefore, even the leeward shoreface and nearshore areas of Cat Island in the vicinity of Pigeon Cay are frequently agitated by waves and are likely sites of recent ooid formation.

These interpretations agree with the model of ooid formation under wind-generated wave agitation on the Caicos Platform (Lloyd et al., 1987; Wanless and Tedesco, 1993; but see also Rankey and Reeder, 2010). There, regular concentric ooids form in shallow subtidal and shoreface settings along coastlines facing the platform interior and indicate that bottom agitation by waves can provide conditions

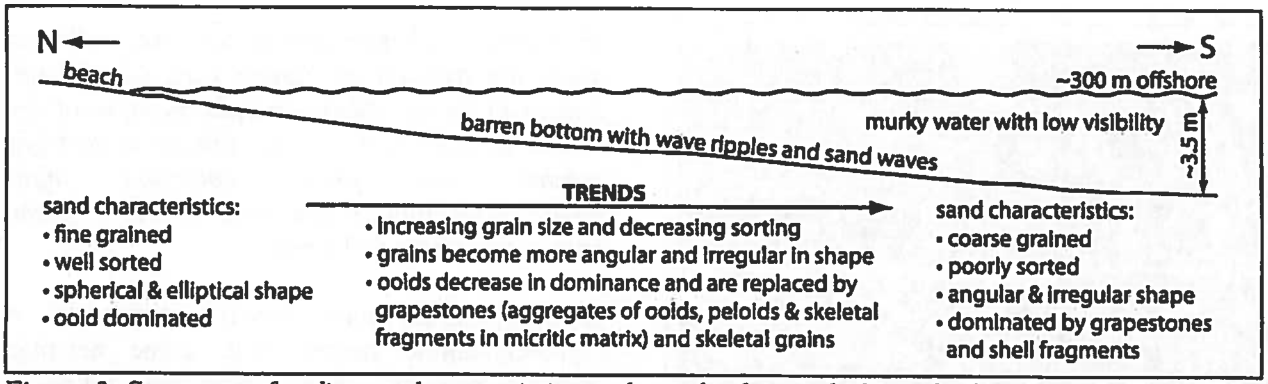
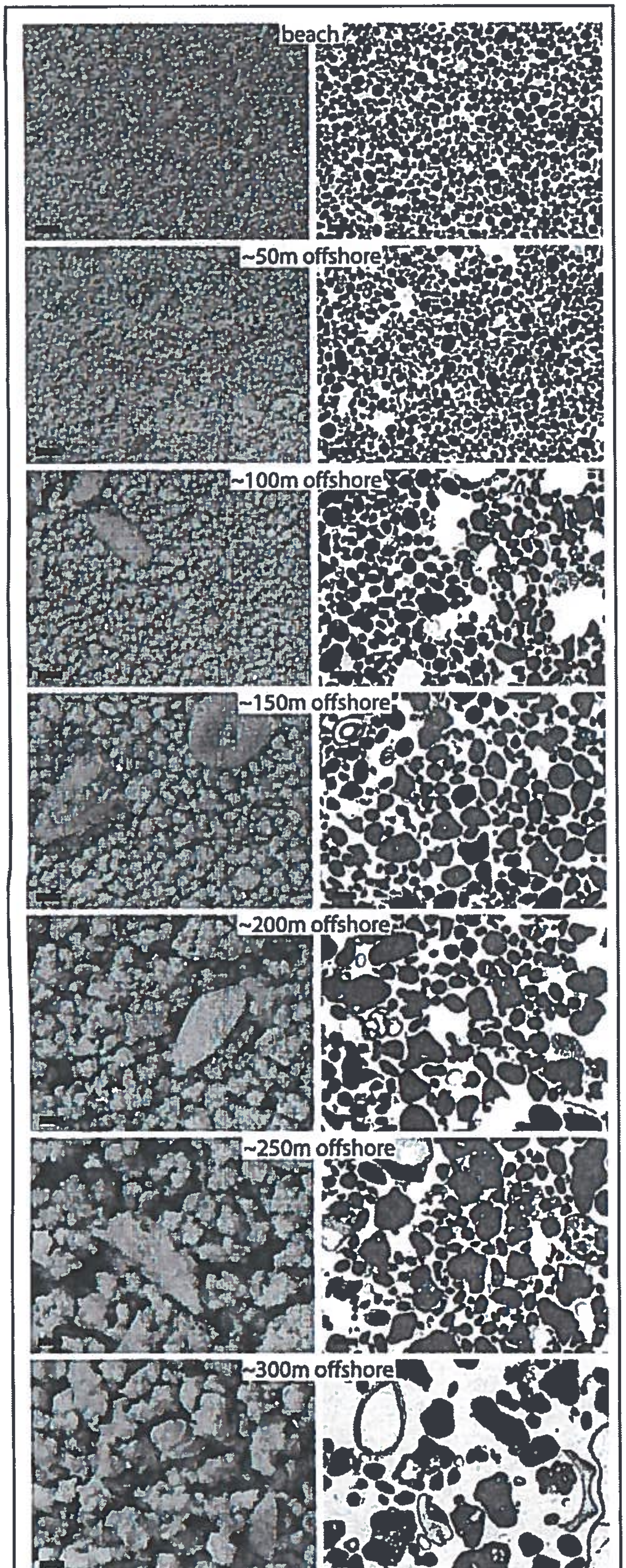


Figure 3. Summary of sediment characteristics and trends observed along the beach to shallow offshore transect at Pigeon Cay, Cat Island.

favorable for ooid sand formation in leeward settings. Along such coastlines, sediment is quite similar to that observed on Pigeon Cay: ooids are commonly mixed with peloids, some of the ooids are highly micritized, and many of the peloids are simply completely micritized ooids (Lloyd et al., 1987). In addition, ooids that form along the beach (mainly intertidal swash zone) of some low-energy, south-facing embayments of the Caicos Platform interior are very similar to those from the Pigeon Cay beach: ooids are regular concentric, with nuclei composed predominantly of peloids and micritized grains, and are rather small (mainly <200 μm). On the Caicos platform, ooids occur on the sloping shoreface and adjacent very shallow bay bottom and decrease in abundance seaward. We documented the same trends at Pigeon Cay (Figures 3 and 4).

The examples from the Caicos Platform demonstrate that wave agitation can generate oolitic sediment bodies even in low-energy settings if other conditions are ideal, i.e. sufficiently supersaturated waters, water renewal, low influx of other grain types, and lack of sediment stabilization (e.g., Wanless and Tedesco, 1993). All of these conditions seem to be met in the Pigeon Cay area of Cat Island where ooids are forming on the leeward side of the island on the beach shoreface and in a narrow mobile fringe just offshore. The low input of skeletal material is related to the absence of calcareous algae and corals in this setting. Previous studies of the sediment distribution on the Cat Island shelf reported that skeletal allochems are locally generated in association with poorly developed reefs and that the overall abundance and quality of preservation of skeletal fragments increase with water depth toward the bank edge (Dominguez et al., 1988). We observed the same trend in skeletal material distribution and preservation along our 300 m nearshore sediment transect at Pigeon Cay.

The study of the Cat Island shelf by Dominguez et al. (1988) focused on deeper water (mainly 6 to 100 m depth), but their sediment distribution map encompasses the entire west coast of Cat Island, even though it is not apparent that they conducted beach surveys. Only 2 of their 77 samples were collected nearshore, and the sampling site closest to our Pigeon Cay study area was about 2 km offshore in water >6 m deep. In their study, Dominguez et al. (1988) did not specifically mention ooids, but they documented "cryptocrystalline grains" as the most abundant and widespread grain type on the Cat Island shelf. These grains were found to be particularly common in relatively shallow depths and restricted to the inner to mid shelf in protected areas <10 m deep, where grains are repeatedly bored and degraded beyond recognition (Dominguez et al., 1988). Their description and SEM images of the "cryptocrystalline grains" suggest that they are likely peloids and/or micritized ooids. The second most common Cat Island shelf-grain type, as documented by Dominguez et al. (1988), are aggregate grains of subrounded



← Figure 4. Photographs of sediment collected along the transect at Pigeon Cay, Cat Island. Images in the left column are photographs of dry sediment; scale bars = 1 mm. Images in the right column are plain polarized light photomicrographs of sediment mounts in clear epoxy; scale bars = 0.5 mm.

cryptocrystalline and skeletal grains in a cryptocrystalline matrix with some acicular aragonite cement. These grains were found in environments that provide sufficient winnowing of mud, but are protected enough to shield sand from active transport. This grain type seems identical to our grapestone aggregates, and their distribution is in agreement with our observation that they form in deeper, less energetic water by lithification of oolitic, peloidal and skeletal sand in a micritic matrix and with some marine aragonite cement. The overall paucity of mud in the sediment is likely related to winnowing by currents and also to effective removal of micrite by its lithification into aggregates (e.g., Rankey and Reeder, 2010).

The coast and offshore area surrounding Alligator Point and encompassing our Pigeon Cay study area was shown on the sediment distribution map of Dominguez et al. (1988) as dominated by carbonate lithoclasts. These authors distinguished lithoclasts from aggregate grains by the presence of coarse crystalline cement, surficially coated particles compositionally different from coexisting sediments, and by truncated cement and grains. The lithoclastic facies is distributed perpendicular to the western margin of Cat Island, includes subtidal sand shoals adjacent to cuspate headland barriers where sediment is generally >2 m thick, and is interpreted to reflect a locally eroding coastline (Dominguez et al., 1988). There were no photomicrographs of petrographic thin sections included in Dominguez et al. (1988), but judging from their descriptions and SEM images, it is certain that their "surficially coated" grains represent ooids. Although unclear as to why Dominguez et al. (1988) did not refer to these grains as ooids, it is highly likely that they did not find unaltered ooids because their observations were made in deeper water where these grains were micritized into peloids and/or lithified in aggregates, as is the case along the southern end of our Pigeon Cay transect (Figures 3 and 4). In this part of the transect, we also observed some indurated aggregate grains or lithoclasts with truncated ooids and rare, clear equant cement of likely meteoric origin. This supports the interpretation of an eroding coastline as the source for these clasts. Since lithoclasts are not the dominant component of sediment at Pigeon Cay and are present in deeper offshore water, we suspect that they may be derived from local Pleistocene outcrops eroded and buried during the Holocene transgression.

Overall, our study indicates that small islands surrounded by shallow marine carbonate-producing environments can provide sites of nearshore agitation for ooid generation even in areas of moderate to gentle winds. The Boiling Hole area of Eleuthera Island and Fernandez Bay on Cat Island where ooids were formed on the bank interior and transported directly onto the island by a westerly flux represent additional Bahamian Pleistocene and Holocene examples, respectively (Kindler, 1992; Kindler et al., 2008; Kindler and Hine, 2009).

Our reconnaissance observations of various beaches on Cat Island revealed a large variation in sand composition from predominantly oolitic at Pigeon Cay to mainly skeletal in other areas. Such peculiar distribution of ooid sand on Cat Island warrants future in-depth examinations involving beach surveys, sediment collection along many more transects (including longer, cross-shelf transects), determination of the ages of ooids, thickness of ooid deposits and their lateral distribution, as well as monitoring wave and current conditions.

CONCLUSIONS

Observations of sediment distribution along a beach to offshore transect at Pigeon Cay, Cat Island, Bahamas suggest that ooids are currently forming in the shoreface and shallow (less than about 2 m deep) nearshore environment extending about 200 m offshore and characterized by a barren bottom with sand sculpted into wave ripples and sand waves. Along this leeward-facing beach, moderate to gentle and largely intermittent wave energy and the absence of abundant input of skeletal sediment provide conditions that support the formation of ooid-dominated sediment. This sediment can be transported onshore and lithified into beachrock and eolianite. Ooids are also transported offshore, where in deeper and less energetic water they are lithified into grapestone aggregate grains together with skeletal fragments, peloids (largely micritized ooids) and carbonate mud. Although preliminary, our observations on Cat Island provide new insights into the present-day production and deposition of ooids along leeward sides of small Bahamian islands by documenting the presence of a narrow, wave-swept shallow offshore area generally devoid of metazoan sediment stabilizers where ooids form and are subsequently transported in both onshore and offshore directions.

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